AN IMPROVED TWO-PHASE PRESSURE DROP CORRELATION FOR 180° RETURN BENDS

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ABSTRACT

A new correlation for two-phase flow pressure drop in 180° return bends is proposed based on a total of 241 experimental data points for R-22 and R-410A. The data span smooth tubes with inner diameters (D) from 3.25 mm to 11.63 mm, bend radii (R) from 6.35 mm to 37.25 mm, and curvature ratios ($2R/D$) from 2.32 to 8.15. The correlation predicts all data with a mean deviation of 15.7 %, and 75 % of the data fall within ± 25 % error bands.

NOMENCLATURE

$a_0 \ldots a_4$	constants in equation 7
B	straight-tube length between neighboring tubes
$\mathrm{d}p/\mathrm{d}l$	pressure gradient: in equations [Pa m^{-1}]
	: in figures [kPa m^{-1}]
D	inner diameter [m]
f	friction factor
G	refrigerant mass flux [kg s^{-1} m^{-2}]
L	bend length [m]
p	pressure [Pa]
R	bend radius [m]
Re	Reynolds number
We	Weber number
x	vapour quality

Greek letters

Λ	curvature multiplier
μ	absolute viscosity [Pa s]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]

Subscripts

k	liquid phase or vapour phase
l	liquid phase
$r\text{-}b$	return bend
$s\text{-}t$	straight tube
v	vapour phase

INTRODUCTION

Return bends are curved pipe fittings which connect parallel straight tubes in finned-tube heat exchangers, such as evaporators and condensers used in air-conditioning and refrigeration systems. The two-phase flow region occupies the major part of these coils. The pressure drops in the return bends may be of the same magnitude as those observed for straight tubes. Figure 1 shows a schematic of a return bend.

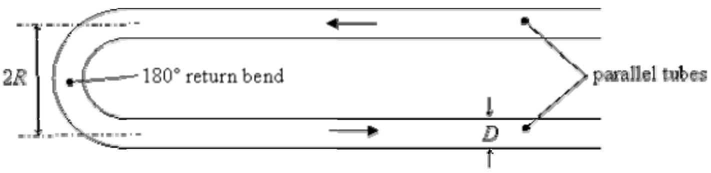

Fig. 1 Schematic of a 180° return bend

The first study on two-phase pressure drop in return bends is attributed to Pierre [1] who proposed a correlation based on experiments carried out with R-12 and R-22. Geary [2] studied pressure drop of R-22 using various bend geometries and indicated the importance of the centre-to-centre distance. Chisholm [3] and Paliwoda [4] proposed correlations for two-phase pressure drops in return bends although they did not provide validation of their correlations against experimental data. Recently, Chen et al. [5] and Chen et al. [6] studied flows involving water-air mixtures and R-410A, respectively, through different bend geometries.

In the present work, a set of 241 experimental data points obtained from Geary [2] and Chen et al. [6] was used to derive a new, improved correlation that can be applied within the whole two-phase region for smooth-tube return bends. All refrigerant property calculations were based on REFPROP [7].

AVAILABLE EXPERIMENTAL DATA AND CORRELATIONS

Geary's [2] Database and Correlation

Geary [2] conducted experiments with two-phase, adiabatic flows of R-22 at 4.5 ^{o}C for bends with inner diameters of 11.38 mm to 11.63 mm, curvature ratios from 2.32 to 6.55, vapour-quality range from 0.2 to 0.8, and mass fluxes from 100 kg s^{-1}m^{-2} to 500 kg s^{-1}m^{-2}, for a total of 145 data points. He tested two bends assembled in series and separated by a 190D length tube. He correlated the two-phase pressure drop by using a single-phase pressure drop equation for vapour flow only:

$$\Delta p = f \frac{L}{D}\frac{G^2 x^2}{2\rho_v} \tag{1}$$

where the dimensionless friction factor f is given by:

$$f = \frac{\mathrm{a}\,\mathrm{Re}_v^{0.5}}{\exp\left(0.215\frac{2R}{D}\right)x^{1.25}} \tag{2}$$

In the above equation, a=8.03x10^{-4}, and $\mathrm{Re}_v = xGD/\mu_v$ is the vapour Reynolds number. (Note that Geary's paper uses a=5.58x10^{-6} [ft^2 in^{-2}] to compensate for the British units he selected to use in Eq. (1). Consequently, Geary's friction factor is not dimensionless).

Chen et al.'s [6] Database and Correlation

Chen et al. [6] conducted experiments with two-phase, adiabatic flows of R-410A at 10 ^{o}C and 25 ^{o}C saturation temperatures spanning the vapour qualities from saturated liquid to saturated vapour. The inner diameters varied from 3.25 mm to 5.07 mm, the curvature ratios were from 3.91 to 8.15, and the mass fluxes were from 100 kg s^{-1}m^{-2} to 900 kg s^{-1}m^{-2}. The test section comprised nine bends located in one plane, connected in series in a serpentine configuration.

Based on Geary's [2] and their own data, Chen et al. [6] proposed a correlation which uses the formulation presented by Geary (1975) with a modification to the friction factor correlation. They included the Weber number, $\mathrm{We}=G^2D/\rho_v\sigma$, to account for the effects of liquid surface tension and gas inertia, and replaced the vapour Reynolds number by a combined vapour and liquid Reynolds number, $\mathrm{Re}_m=\mathrm{Re}_v+\mathrm{Re}_l$ ($\mathrm{Re}_v=xGD/\mu_v$, $\mathrm{Re}_l=(1-x)GD/\mu_l$), which yielded:

$$f = \frac{10^{-2}\,\mathrm{Re}_m^{0.35}}{\mathrm{We}^{0.12}\exp\left(0.194\frac{2R}{D}\right)x^{1.26}} \tag{3}$$

A total of 132 tests points from the study by Chen et al. [6] were made available to the authors for three out of four geometries tested Chen [8]. Table 1 presents details of these three bend arrangements.

Table 1 Bend geometries tested by Chen et al. [6]

	Bend #1	Bend #2	Bend #3
D, mm	3.3	3.25	5.07
R, mm	13.45	6.35	13.15
B, mm	23.5	24.5	23
$2R/D$	8.15	3.91	5.19
B/D	7.12	7.54	4.54
# data points	60	36	36

Figure 2 compares Geary's [2] and Chen et al.'s [6] experimental data with the predictions by the Chen et al. [6] correlation. The mean deviation of predictions is 19.1 % with most of the data located within the ±50 % error bands.

IMPROVED CORRELATION

We propose a new correlation based on the two-phase pressure drop correlation for straight tubes by Muller-Steinhagen & Heck [9] and a multiplier which accounts for the bend curvature. The Muller-Steinhagen & Heck [9] correlation predicts the two-phase pressure drop in a straight tube based on the pressure drops of liquid and vapour phases, which are calculated separately.

$$\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_k = 2\frac{f_k}{D}\frac{G^2}{\rho_k} \tag{4}$$

where f_k=0.079 $\mathrm{Re}_k^{-0.25}$, $\mathrm{Re}_k = GD/\mu_k$, and k represents either v or l.

The pressure drops computed for each phase are combined:

$$\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{s-t} = \left[\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_l + 2x\left(\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_v - \left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_l\right)\right](1-x)^{1/3} + \left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_v x^3 \tag{5}$$

We propose that the pressure drop in the return bend to be calculated by applying a "curvature" multiplier, Λ, to the straight-tube correlation:

$$\left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{r-b} = \Lambda \left.\frac{\mathrm{d}p}{\mathrm{d}l}\right|_{s-t} \tag{6}$$

We derived the curvature multiplier Λ via the Buckinham-PI Theorem using four dimensionless groups. The first term is the vapour Reynolds number accounts for the influence of vapour velocity, xG/ρ_v, while the second and the third terms are related to mass distribution for each phase. The last term accounts for the effects of the bend curvature.

$$\Lambda = \mathrm{a}_0\left(\frac{GxD}{\mu_v}\right)^{\mathrm{a}_1}\left(\frac{1}{x}-1\right)^{\mathrm{a}_2}\left(\frac{\rho_l}{\rho_v}\right)^{\mathrm{a}_3}\left(\frac{2R}{D}\right)^{\mathrm{a}_4} \tag{7}$$

where the coefficients, determined from the Least Squares Method, are given in Table 2 in column (A).

Figure 3 plots the pressure drop predictions for all available experimental data using the coefficients from column (A). While the agreement between the measurements and correlation is generally good, the correlation underpredicts several points for bend #3 from the Chen et al. [6] database. We note that, in the #3 experimental arrangement, the straight tubes connecting the subsequent bends had a straight length of approximately four tube diameters, while Hoang & Davis [10] suggested that a length equal to nine tube diameters is required to completely mix the phases after leaving a return bend. We thus speculate that the connection tubes were too short in the #3 configuration to allow the flow to re-establish the straight-tube flow pattern, and thus resulted in a larger return-bend pressure drop than would be measured otherwise. The straight-tube lengths for the #1 and #2 test configurations corresponded to approximately eight tube diameters.

Since the heat exchangers used in air conditioning and refrigeration have long tubes (much longer than 9 tube diameters) that allow the refrigerant to re-establish its straight-tube flow pattern after leaving the return bend, we removed bend #3 data from the database and refitted the constants in Eq. (7). Table 2 includes the new constants in column (B), and Figure 3 shows the pressure drop predictions using these constants.

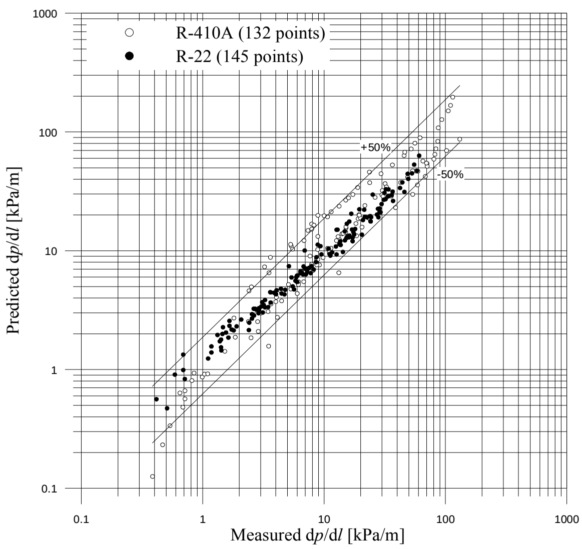

Fig. 2 Comparison of all data with predictions by the Chen et al. [6] correlation

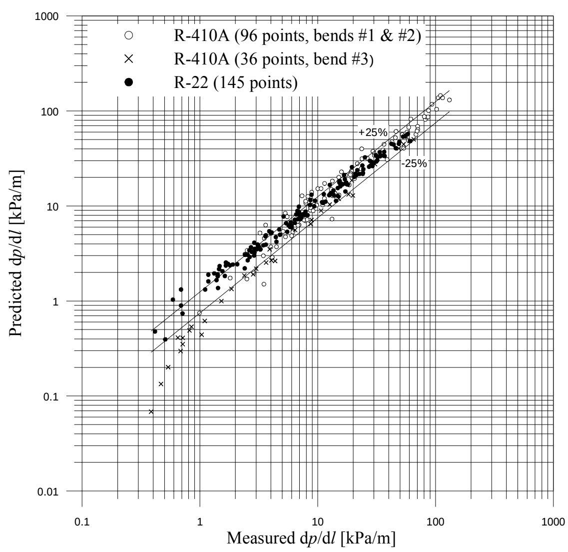

Fig. 3 Comparison of all measurements with predictions by the new correlation (A)

Table 2 Fitted coefficients for Eq. (7)

Coefficient	(A) 277 points - all points	(B) 241 points - all points except bend #3
a_0	5.2×10^{-3}	6.5×10^{-3}
a_1	0.59	0.54
a_2	0.22	0.21
a_3	0.27	0.34
a_4	-0.69	-0.67

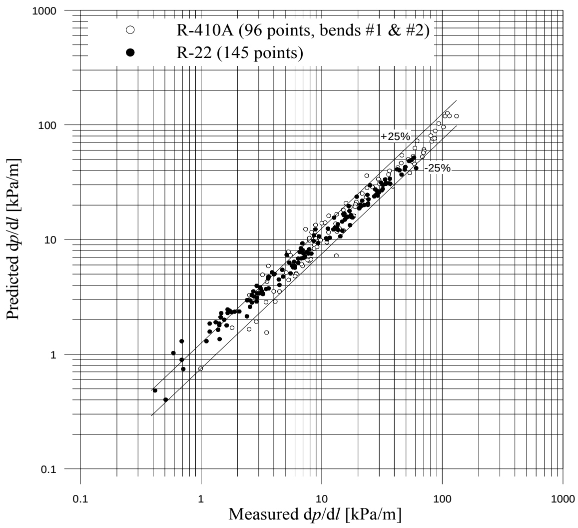

Fig. 4 Comparison of 241 data points with predictions by the new correlation (B)

CONCLUSIONS

An improved correlation for pressure drop in return bends was developed using 145 data points for R-22 and 96 points for R-410A from two different experiments. The new correlation predicts 75 % of the experimental data points within ±25 % error bands with a mean deviation of 15.7 % for all the data.

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